Lithos 112S (2009) 465–472

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

The importance of the transport system in shaping the growth and form of kimberlite volcanoes

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ARTICLE INFO

Article history:
Received 29 September 2008
Accepted 10 April 2009
Available online 3 May 2009

Keywords:
Kimberlites
Diatremes
Diamonds
Transport processes
Sorting
Phreatomagmatism

ABSTRACT

Understanding the range of transport styles recorded by kimberlite deposits is key to describing the type and style of eruptions. Building a clear picture of the processes that shape deposits is essential for selecting exploration targets and evaluating the grade and value of diamond-bearing kimberlites. Variations in grade reflect differences in the diamond content of different magma parcels erupted during the lifetime of the kimberlite volcano, sorting during transport of eruption products, or reworking of diamonds during crater growth, cone collapse and erosion.

The form of the kimberlite volcano is largely determined when the magma arrives near the surface. If magma comes into contact with external water, transport will be driven by a combination of magmatic gases + steam. From a diamond exploration perspective, the resulting deep diatremes make the most attractive targets because they survive erosion and tend to form large geophysical anomalies. If water is too abundant, a tuff cone or tuff ring with no diatreme or a shallow one will form. On the other hand, if external water is very limited or if the conduit is rapidly sealed by chilled melt, the transport system will be driven by magmatic gases alone. The result will then be a spatter cone or cinder cone underlain by a dike, possibly with a related lava flow, but with no diatreme.

1. Introduction

Transport of kimberlite magma from the mantle to or near the surface is a complex process that involves many, often sudden and dramatic, changes in transport style. The pace and magnitude of changes in the transport system begin to accelerate as the magma nears the surface, culminating in eruptions during which multiple transport events take place simultaneously, and single transport events may change significantly from their point of origin to final deposition. Variations in diamond grade reflect differences in the diamond content of different magma batches erupted during the lifetime of the volcano, sorting during transport of eruption products, or reworking of diamonds during crater growth, cone collapse and erosion. This paper sets out the source and signature of transport events during the evolution of kimberlite volcanoes with an emphasis on distillation of observations from field data, drill cores and thin sections. The discussion is weighted toward transport systems in diatremes and craters because the full spectrum of kimberlite volcanism is not covered by existing field data, although some useful interpretations can be drawn from the few described examples of surface kimberlite deposits as well as by comparison with equivalent small-volume volcanic systems.

2. Deep transport systems control delivery of magma and diamonds to eruption sites

The initial stages of kimberlite transport involve rise of magma in narrow dikes (e.g., Dawson and Hawthorne, 1970). There is compelling evidence that kimberlite magmas are extracted from their source region and erupted without significant residence times in the crust (e.g., Mitchell, 2008). In this respect, kimberlites have much in common with monogenetic continental volcanoes, each inferred to record short-lived eruption of a single magma batch. On the other hand, careful examination of the volcanic products of monogenetic eruptions, combined with geochemical work on single eruption phases, reveals that many so-called monogenetic volcanoes are in fact composite landforms that record episodic activity at the same site over significant time periods. There is a growing body of evidence that this variation often records ascent of new, unique magma batches from the mantle (Nemeth et al., 2003; McClintock et al., 2008a).

Likewise, many single kimberlite volcanoes have significant variations in diamond grade between different kimberlite phases, suggesting eruption of distinct (perhaps unrelated) magma parcels at the same site. In some kimberlites, different magma batches were

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doi:10.1016/j.lithos.2009.04.014

erupted at the same site during short-lived pulses of activity separated by long periods of volcanic quiescence. For example, single kimberlite complexes in the Fort à la Corne field in Canada have been constructed by at least seven brief episodes of activity over a period of 5 to 7 million years (Kjarsgaard et al., 2006, this issue). Persistent re-occupation of the deep magma transport system by kimberlite melts suggests that stable, deeply tapping magma pathways are the key feature of the deep kimberlite transport system.

3. Shallow transport systems shape volcanoes

The deposits described to date indicate that emplacement of kimberlite involves processes that range from intrusion of shallow sills, sheets and dikes to violent eruptions that quarry deep diatremes into hard rocks. Tuff cones and rings constructed by eruptions of kimberlite magma have been described from Fort à la Corne (e.g., Leckie et al., 1997; Zonneveld et al., 2004; Lefebvre and Kurszlaukis, 2008). Kimberlite scoria cones and lava flows are rare but the examples described to date are made up of deposits much like scoria and lava formed by other mafic to ultramafic magma types (e.g., Reid et al., 1975; Dawson, 1994). It is unlikely that the range of kimberlite volcanoes preserved in the rock record today, made up of many diatremes and intrusions and very few volcanic cones and lavas, is representative of the range that forms in nature.

3.1. Transport within diatremes

Because of their common characteristic geophysical signature contrast relative to host rocks and excellent preservation potential in continental terrains, and thus often significant preserved volume, diatremes represent the favoured primary target for diamond explorers. Understanding the processes that shape kimberlite diatremes is essential to accurately evaluate the grade of diamond deposits and to target high-grade parts of large or marginally economic kimberlite bodies. Diatremes form during eruption of the full spectrum of magma compositions and have been well studied (e.g., Hearn, 1968; Lorenz, 1975, 1979, 1986; White, 1991; Lorenz, 2003). Comparison of diatremes formed during eruption of basalt, for example, is valid because all diatremes formed by any magma composition share many features in common (see below). In fact, to our knowledge there are few, if any, features that are unique to kimberlite diatremes. The simplest explanation for this range of shared features is that the same processes act to form kimberlite diatremes and diatremes of other magma composition.

In the absence of significant erosion, diatremes are overlain by maar craters (Fig. 1a and b). The maars are surrounded by tephra rims, which are typically rich in country rock fragments when erupted through hard rocks (Fig. 1c). Diatremes can range from small bodies tens of metres deep that may merge at depth with irregular "budded" dikes to deep funnel-shaped structures that extend for hundreds to thousands of metres below the surface (Hawthorne, 1975; Mitchell, 1986; Clement and Reid, 1989). Although some diatremes have symmetrical cross-sections and form regular inverted cone-shaped bodies, many diatremes have very irregular shapes that reflect local structural controls or coalescence of two or more adjacent structures. Extreme examples of diatreme coalescence have produced laterally extensive "nested" diatreme complexes that are tens of square kilometres in area (e.g., Coombs Hills, Antarctica: McClintock and White, 2000; White and McClintock, 2001; McClintock and White, 2006; Ross and White, 2006).

Diatremes are problematic to interpret because (i) the eruptions are not observable in the below-ground part of the system; and (ii) the deposits that fill diatremes are often structureless – especially in their lower parts – and thus contain few sedimentological clues to guide reconstruction of their formation. Unravelling the characteristics of the transport system is complex because they simultaneously act as sites of deposition and eruption. It follows that deposits in diatremes record a much better picture of the final stages of diatreme development than they do of the early stages. Some key features are:

1. Non-bedded or very weakly bedded, poorly sorted volcaniclastic deposits, often with a "well-mixed" aspect (incorporating country rock fragments from many stratigraphic levels) that occupy the central and lower parts of the structure (e.g., Kurszlaukis and Barnett, 2003). The upper part of the diatreme can be bedded (e.g., Hearn, 1968).
2. Some diatremes include metre- to tens of metre-scale megablocks of wall-rock that have subsided hundreds of metres below their original stratigraphic position (e.g., Clement and Reid, 1989). Megablocks of syn-eruptive volcaniclastic deposits originally deposited on the ground surface (pieces of the tephra rim) are sometimes found in large diatremes (Fig. 1d). In one example, a quarter of a tephra rim is now enclosed in vent-filling rocks, implying that the small edifice (original radius ~200 m) collapsed downward when it was undermined by a laterally propagating diatreme, and partly subsided into it (Ross et al., 2008a; Fig. 1e).
3. Irregular igneous intrusions tangled with diatreme-filling rocks, mostly preserved in the lower diatreme and the root zone (White and McClintock, 2001). Many dikes and sheets show features consistent with transport of magma into and through diatreme fill soon after it formed (peperite, for example, which implies a wet vent fill) and some dikes extend right through the diatreme fill to feed lava flows and form scoria cones at the surface (Fig. 2a), e.g. Igwisi Hills, Tanzania (Dawson, 1994), or some of the Attawapiskat kimberlites (S. Kurszlaukis pers. comm. 2009).
4. Contacts with wall-rocks vary from sharp to gradational (brecciated) within single diatremes and from one diatreme to adjacent ones. The angle of these contacts is often steep (>60°) but varies from shallow dips to vertical contacts. Variation in the dip and nature of wall-rock contacts is strongly influenced by the strength of country rocks (Lorenz, 2003; Sohn and Park, 2005) and local structural controls (Kurszlaukis and Barnett, 2003).
5. Clasts that record multiple cycles of fragmentation and transport are common (Fig. 2b, c and d).
6. Juvenile clasts are of wide-ranging but mostly low vesicularity, as is the case in tephra rims around maars (Fisher and Schmincke, 1984). This is generally true of all diatremes of any magma composition (e.g., White, 1991; White and Houghton, 2000; Fig. 3). Many diatreme fills include a subset of moderately to highly vesicular clasts, but the majority of juvenile clasts are vesicle-poor (<30% vesicles). We emphasize that non-vesicular to vesicle-poor juvenile fragments are not restricted to kimberlitic diatremes.
7. Welded deposits are rare in diatremes, although welding is common in some surface deposits that overly them (e.g., scoria/spatter cones). Measured and inferred emplacement temperatures in diatremes are significantly cooler than the temperature of erupting magma (e.g., Mitchell, 1986; Stasiuk et al., 1999).

The wide range of vesicularity (≤5% to locally ≥75%) in juvenile clasts within single packages of polymict volcaniclastic rock in diatremes indicates that magma was fragmented at different points in its degassing history (Houghton and Wilson, 1989). Rapid lateral changes in the componentry and grain size of deposits suggest that discrete, repeated transport events involving relatively small volumes of debris were more important than large-volume sustained ones.

Steep internal contacts within diatremes indicate that transport is dominated by sub-vertical movement of vent-filling debris. The fill of some large diatremes can be subdivided into a number of discrete phases distinguished by variation in componentry or diamond grade (in kimberlites) that are bounded by steep contacts (e.g., White, 1991; Ross and White, 2006; Koffiefontein: Naidoo et al., 2004; Finsch, Kimberley, Dutoitspan: Field et al., 2008). These different rock units were emplaced adjacent to each other in stages rather than during a major, more or less continuous pipe-filling event (cf. Sparks et al., 2006; Cas et al., 2008).